Impact of chromatic effects on galaxy shape measurements

Josh Meyers
Pat Burchat

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PSF misestimation

True galaxy gets convolved with PSF;
makes observed galaxy shape bigger and (generally) rounder.

Lensing pipelines attempt to invert this transformation.

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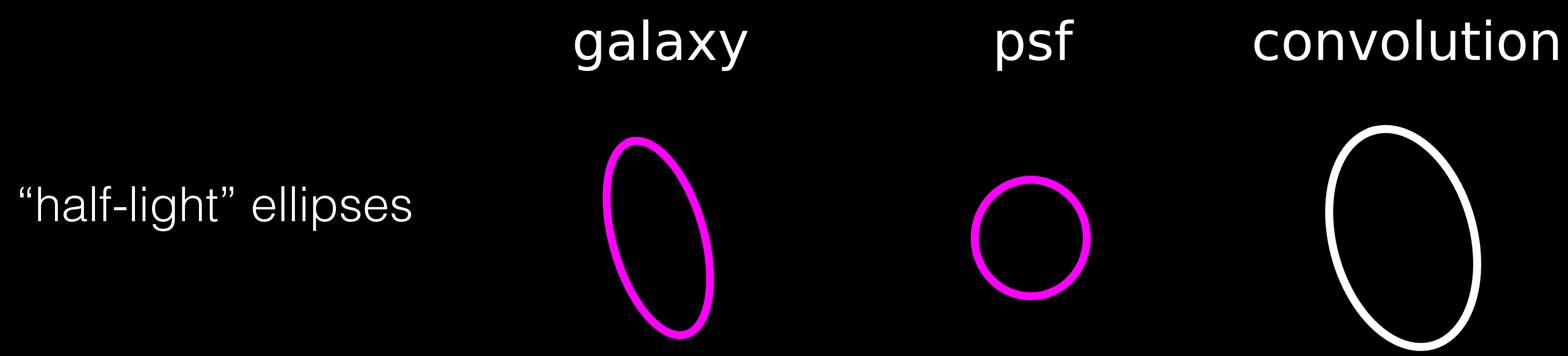

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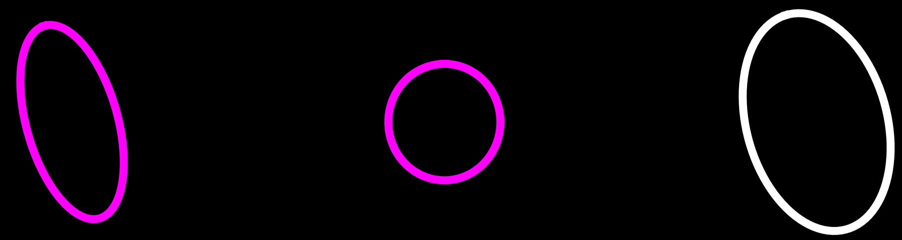

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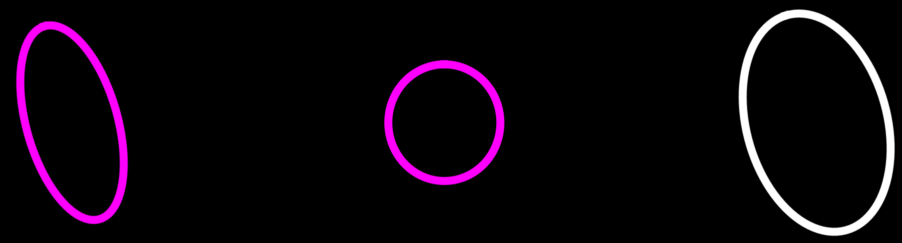

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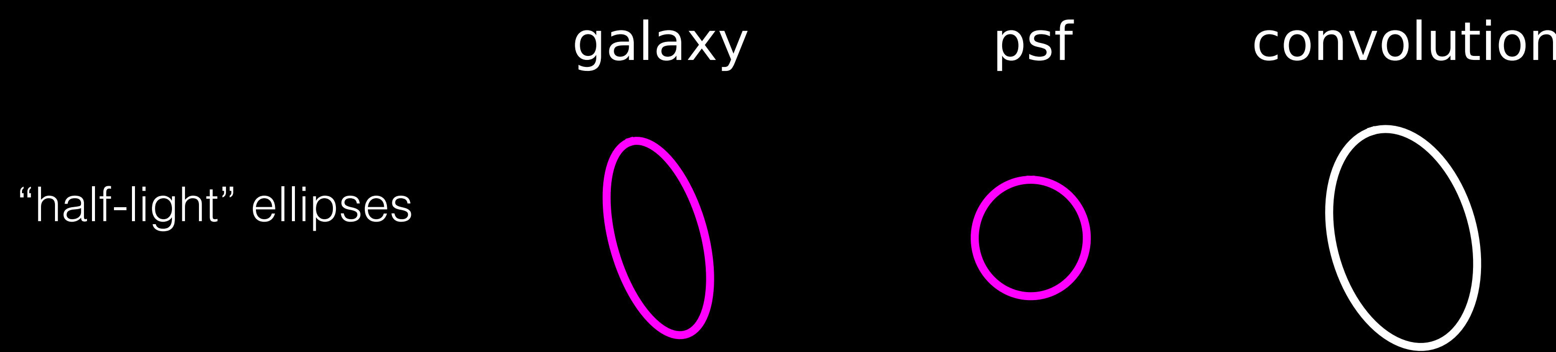

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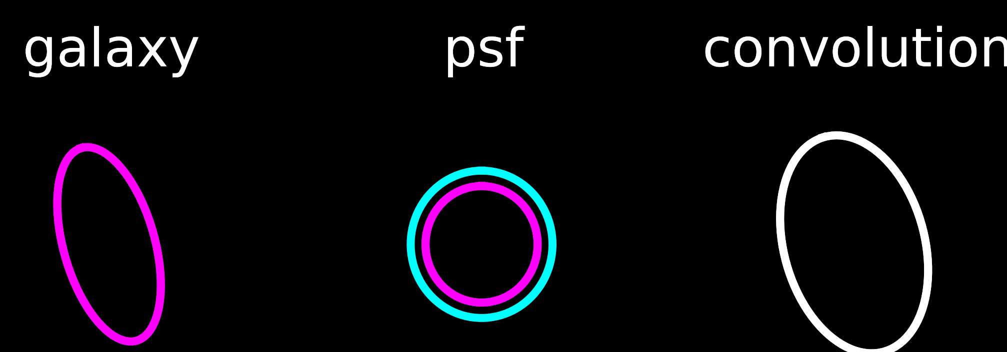

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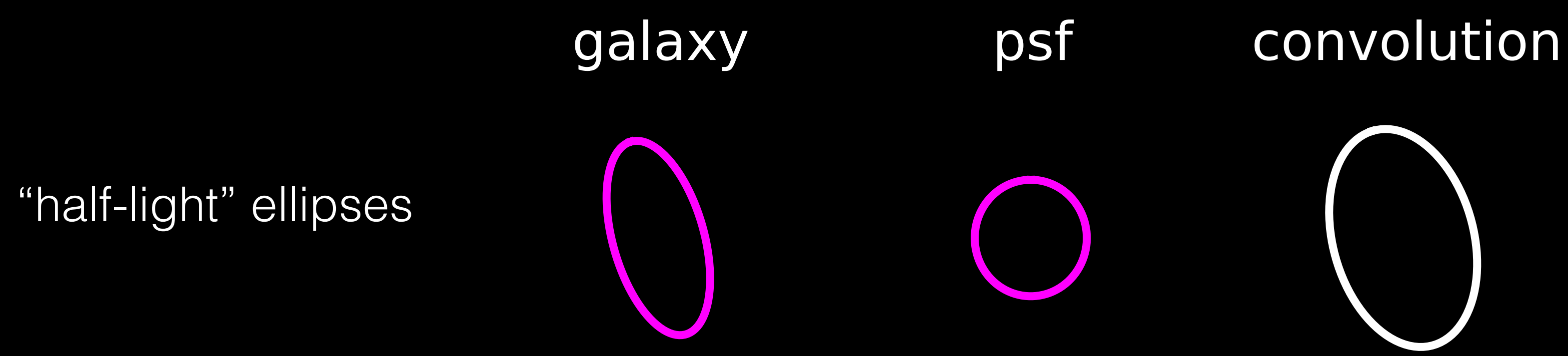

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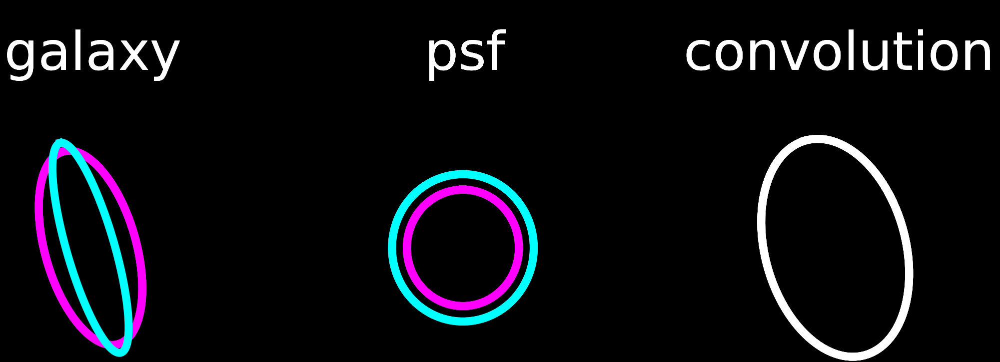

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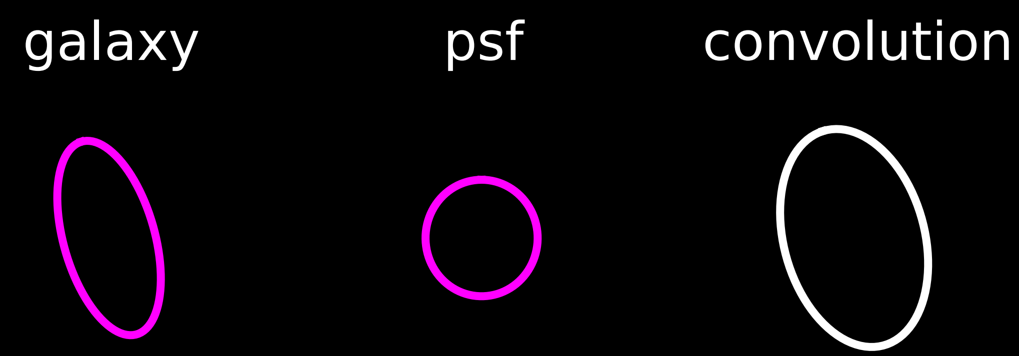

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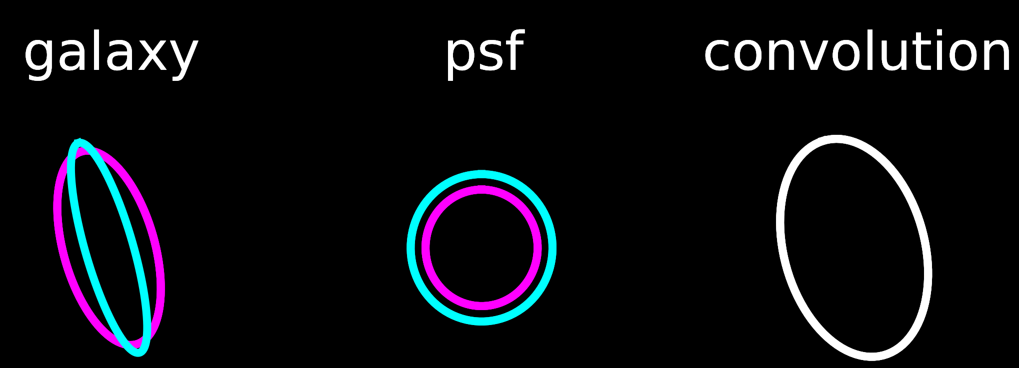

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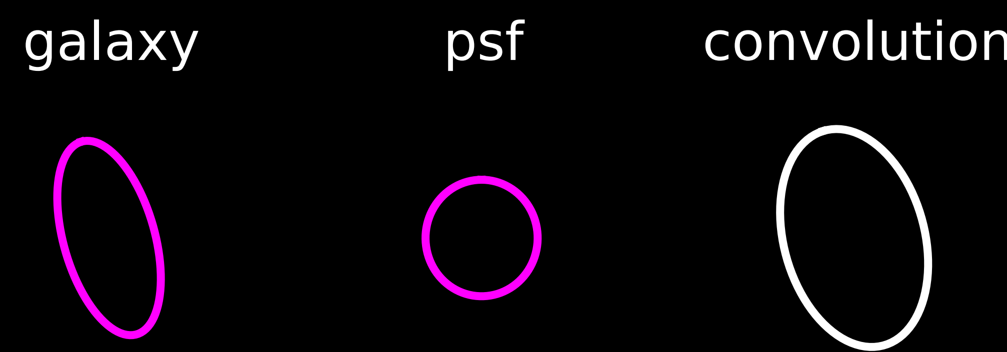

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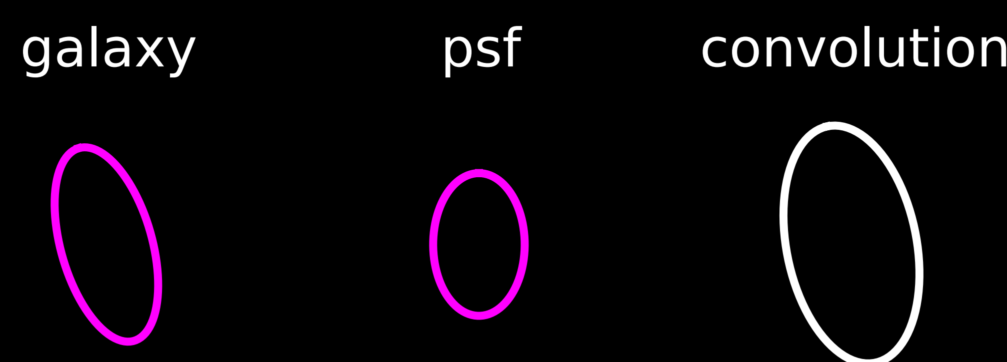

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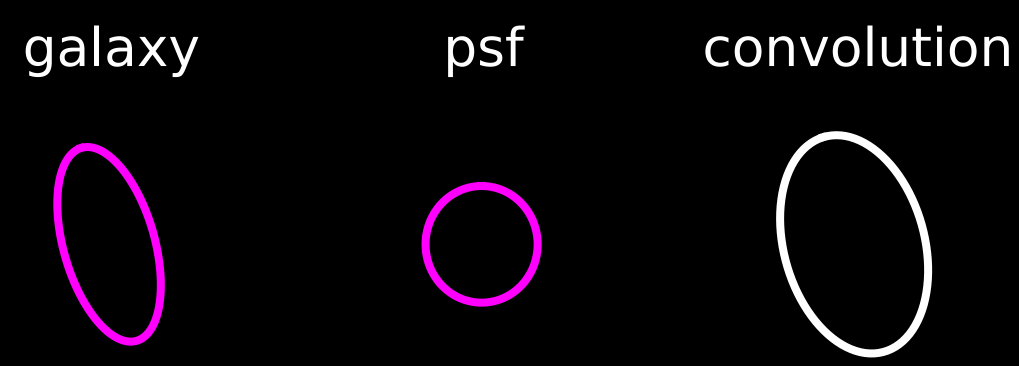

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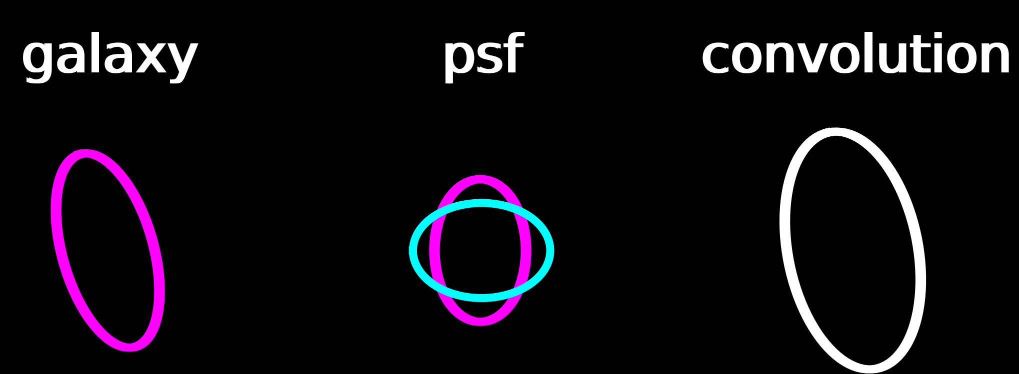

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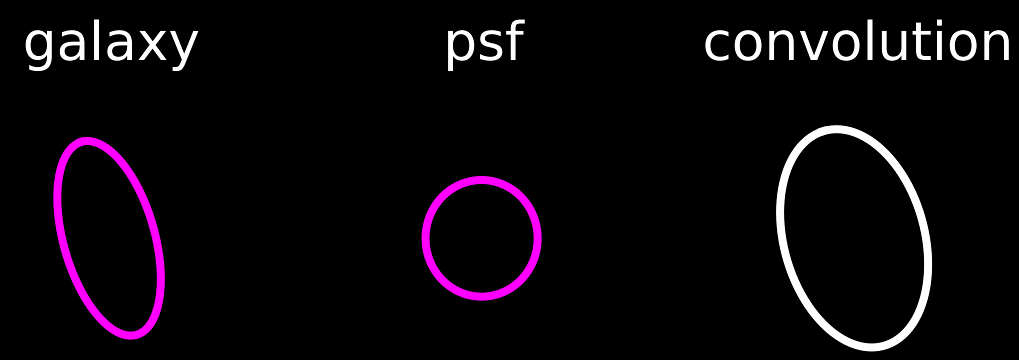

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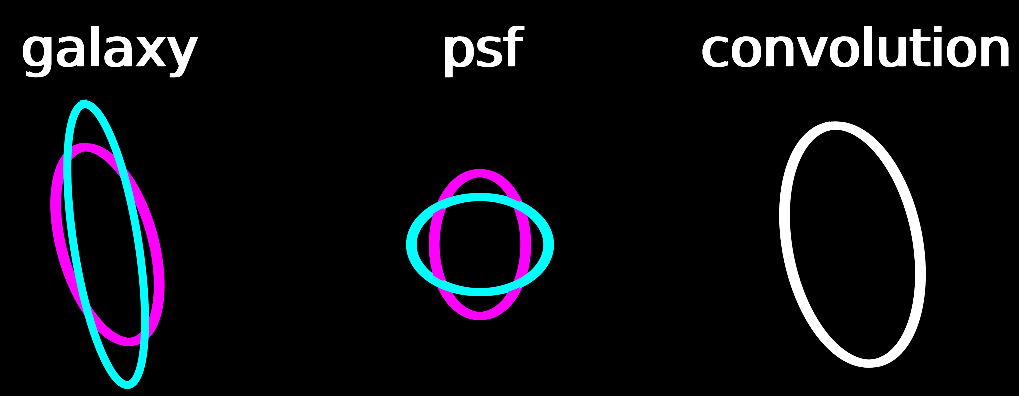

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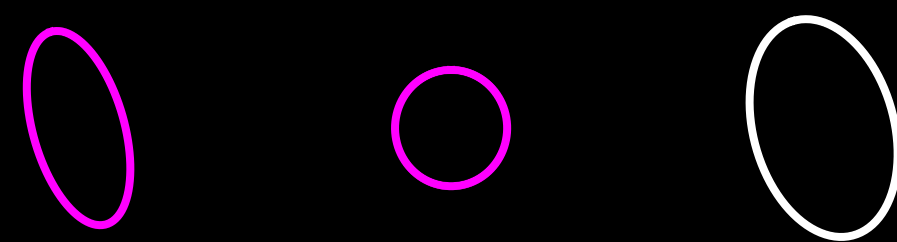

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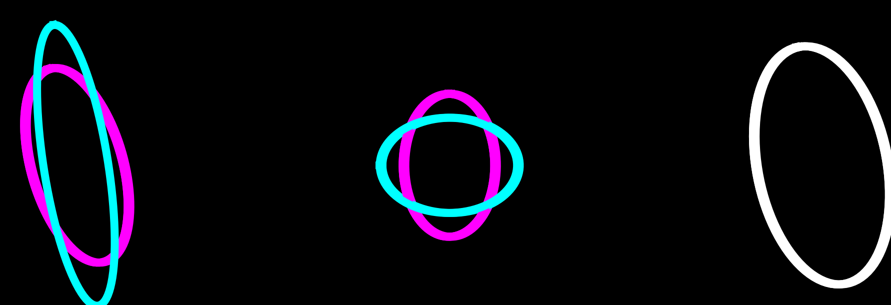

misestimating the PSF ellipticity stretches or squashes galaxy

PSF parameter definitions

Second moments: $$I_{\mu\nu} = \frac{1}{\mathrm{flux}} \int I(x, y)(\mu - \bar{\mu})(\nu - \bar{\nu}) \,\mathrm{d}x \,\mathrm{d}y$$

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Characterizing shear biases: $$\hat{\gamma}_i = \gamma_i(1 + m_i) + c_i$$

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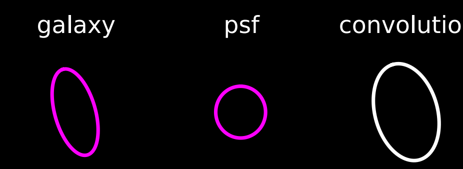
Second moments add under convolution: $I^{\mathrm{obs}} = I^{\mathrm{gal}} + I^{\mathrm{psf}}$



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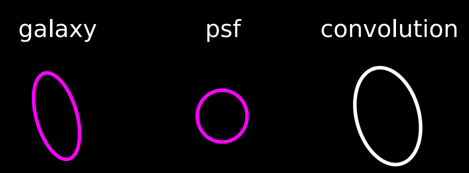

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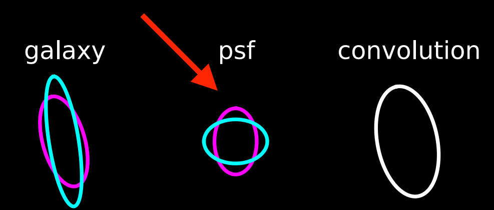
$$\Delta I^{\mathrm{psf}} = I^{\mathrm{psf},*} - I^{\mathrm{psf,g}}$$



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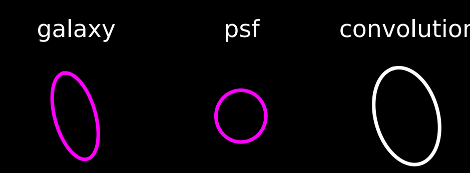

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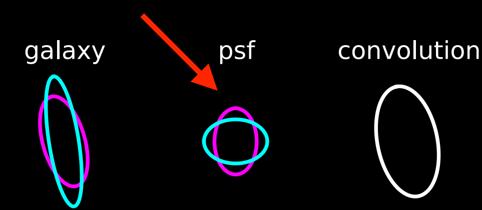
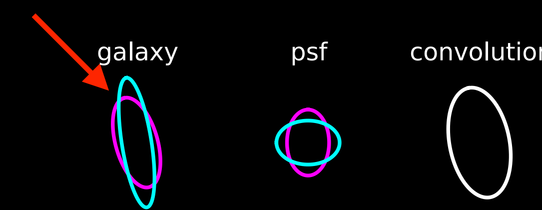


Propagate into ellipticity



$$\epsilon_1 \rightarrow \frac{(I_{xx}^{\mathrm{gal}} + \Delta I_{xx}^{\mathrm{psf}}) - (I_{yy}^{\mathrm{gal}} + \Delta I_{yy}^{\mathrm{psf}})}{(I_{xx}^{\mathrm{gal}} + \Delta I_{xx}^{\mathrm{psf}}) + (I_{yy}^{\mathrm{gal}} + \Delta I_{yy}^{\mathrm{psf}})}$$

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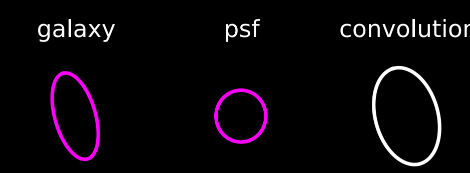

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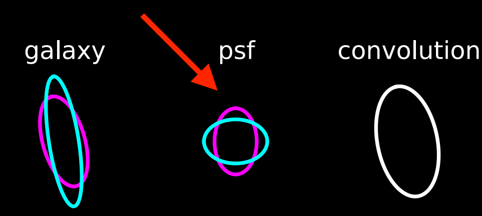

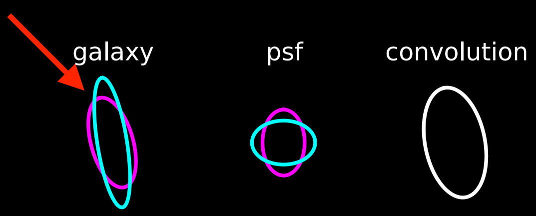

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Algebra

$$\epsilon_1 \to \epsilon_1 \left(1 - \frac{\Delta I_{xx}^{\mathrm{psf}} + \Delta I_{yy}^{\mathrm{psf}}}{r_{\mathrm{gal}}^2}\right) + \frac{\Delta I_{xx}^{\mathrm{psf}} - \Delta I_{yy}^{\mathrm{psf}}}{r_{\mathrm{gal}}^2} + \mathcal{O}\left(\Delta I\right)^2$$

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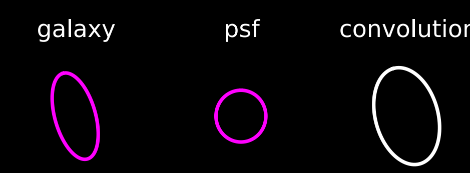

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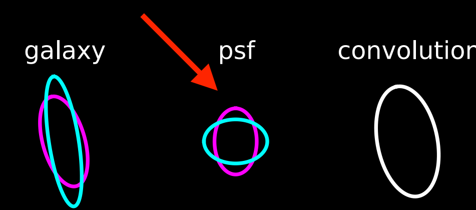

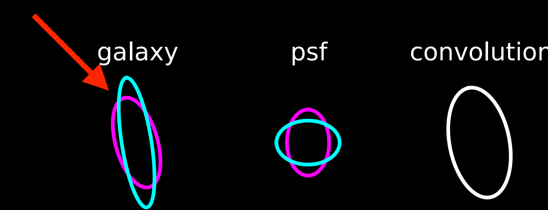

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$$\hat{\gamma}_i = \gamma_i(1 + m_i) + c_i$$

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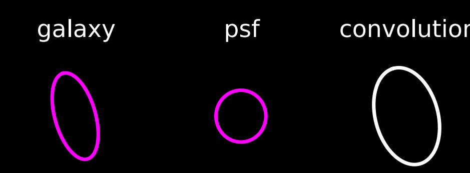

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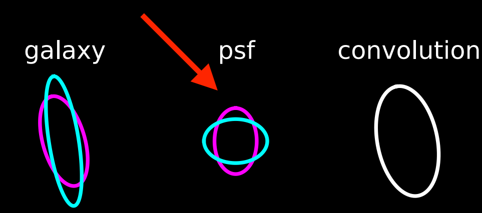

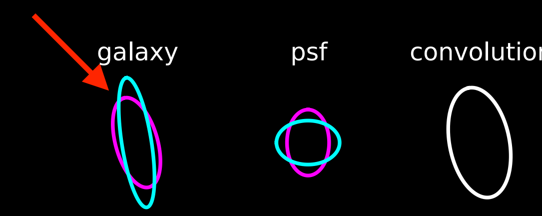

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generic, but assumes unweighted second moments

Some sources of PSF misestimation

- Chromatic effects
  - PSF depends on wavelength
  - Measure PSFs from stars with stellar SEDs.
  - But! PSF affecting galaxy is derived from a galactic SED.

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(same math is relevant for non chromatic effects too!)

- tree-rings
- chip edge effects
- brighter-fatter

Example: brighter fatter effect

- For LSST:
  - $r^2_{gal} \sim (0.3\ \text{arcsec})^2 = 0.09\ \text{arcsec}^2$
  - $I^{PSF}_{xx} \sim 0.12\ \text{arcsec}^2 \Rightarrow \Delta I^{PSF}_{xx} \sim 0.0012\ \text{arcsec}^2$
  - $\Rightarrow m \sim 0.027$
  - compare to $m_{req} \sim 0.003$

Toy model for chromatic CCD PSF effects

Let CCD be chromatic,
but fix atmosphere and telescope to be achromatic.
(not realistic, but useful for isolating CCD effects).

$$I_{\mu\nu}^{\mathrm{PSF}}(\lambda) = I_{\mu\nu}^{\mathrm{PSF,telescope+atm}} + I_{\mu\nu}^{\mathrm{PSF,CCD}}(\lambda)$$

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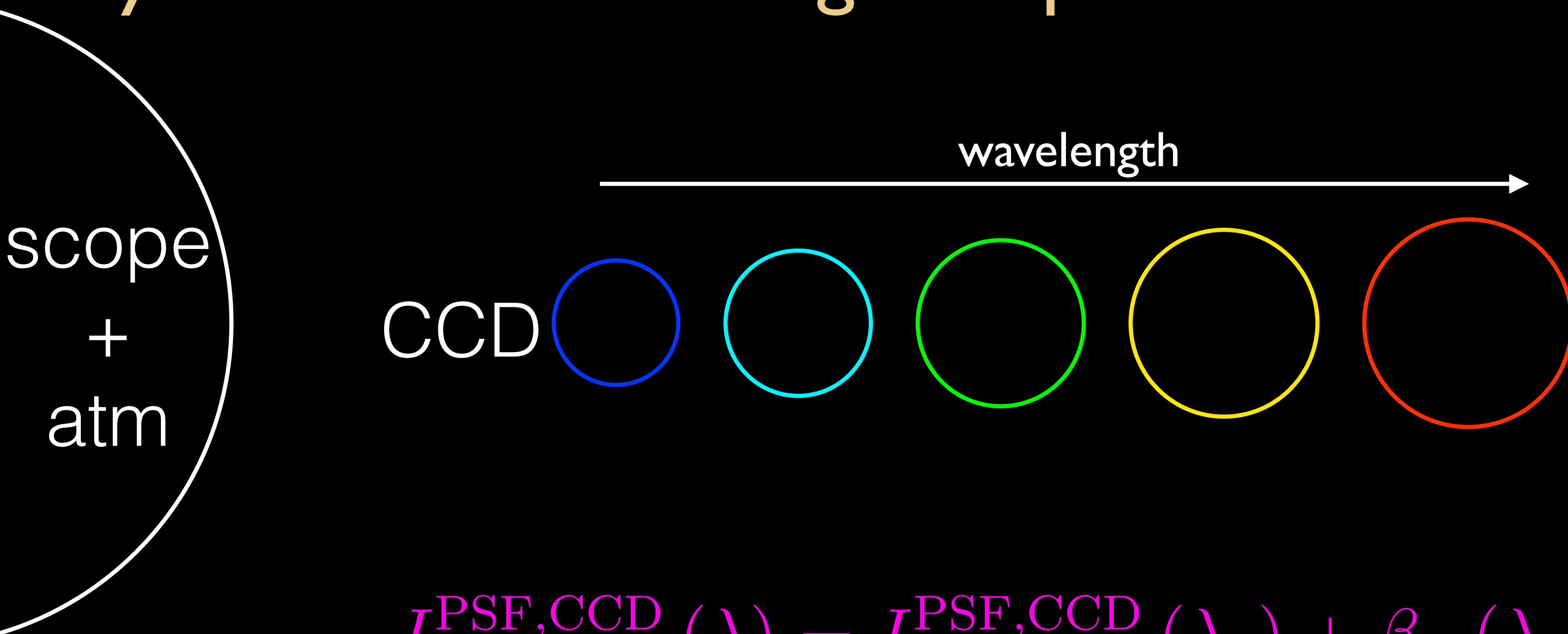
Gaussian w/ FWHM ~0.19 arcsec
I_{xx} ~ 0.0065 arcsec^2

Compute "effective" PSF for a given spectrum/filter.

$$I_{\mu\nu}^{\mathrm{PSF,eff}} = \frac{1}{\mathrm{flux}} \int I_{\mu\nu}^{\mathrm{PSF}}(\lambda)\, \underbrace{R(\lambda)}_{\text{filter}}\, \underbrace{S(\lambda)}_{\text{spectrum}}\, \lambda \,\mathrm{d}\lambda$$

Toy model — wavelength-dependent size



$$I_{xx}^{\mathrm{PSF,CCD}}(\lambda) = I_{xx}^{\mathrm{PSF,CCD}}(\lambda_0) + \beta_+(\lambda - \lambda_0)$$

$$I_{yy}^{\mathrm{PSF,CCD}}(\lambda) = I_{yy}^{\mathrm{PSF,CCD}}(\lambda_0) + \beta_+(\lambda - \lambda_0)$$

Set β_+ such that CCD PSF FWHM is 10% smaller at blue edge of r-band filter than at red edge.

Works out to about 1×10^{-5} arcsec^2/nm or d(FWHM)/dλ ~ 0.14 mas/nm

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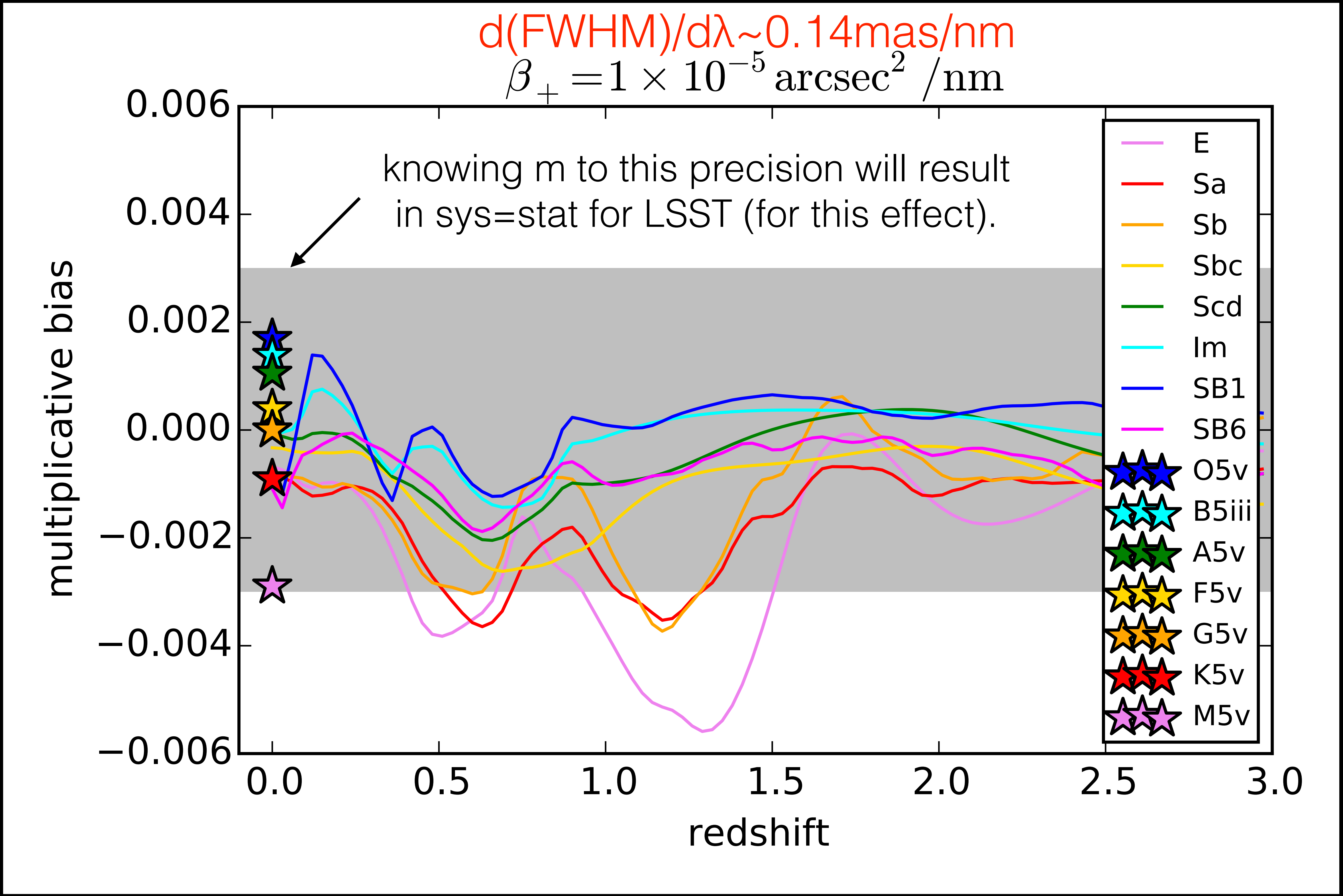
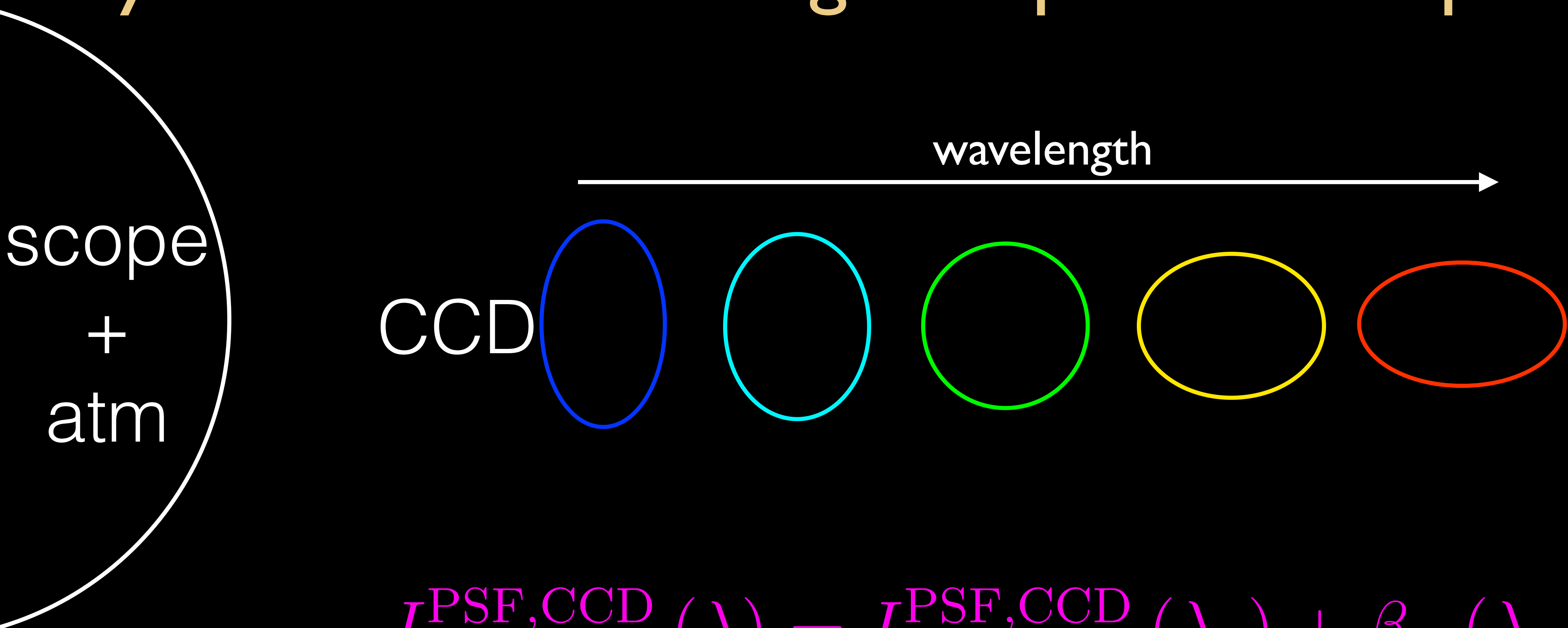


Toy model — wavelength-dependent ellipticity



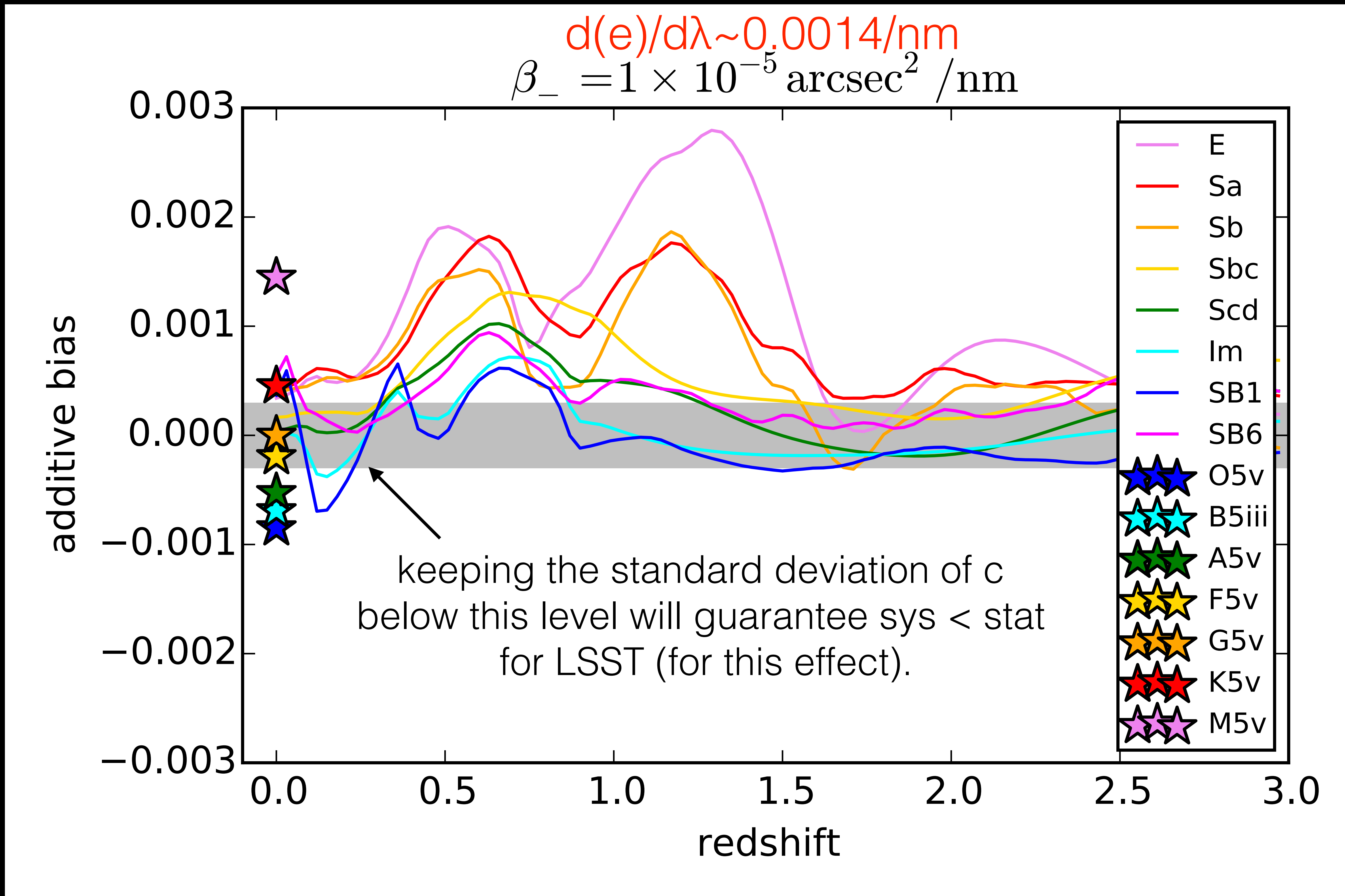
$$I_{xx}^{\mathrm{PSF,CCD}}(\lambda) = I_{xx}^{\mathrm{PSF,CCD}}(\lambda_0) + \beta_-(\lambda - \lambda_0)$$

$$I_{yy}^{\mathrm{PSF,CCD}}(\lambda) = I_{yy}^{\mathrm{PSF,CCD}}(\lambda_0) - \beta_-(\lambda - \lambda_0)$$

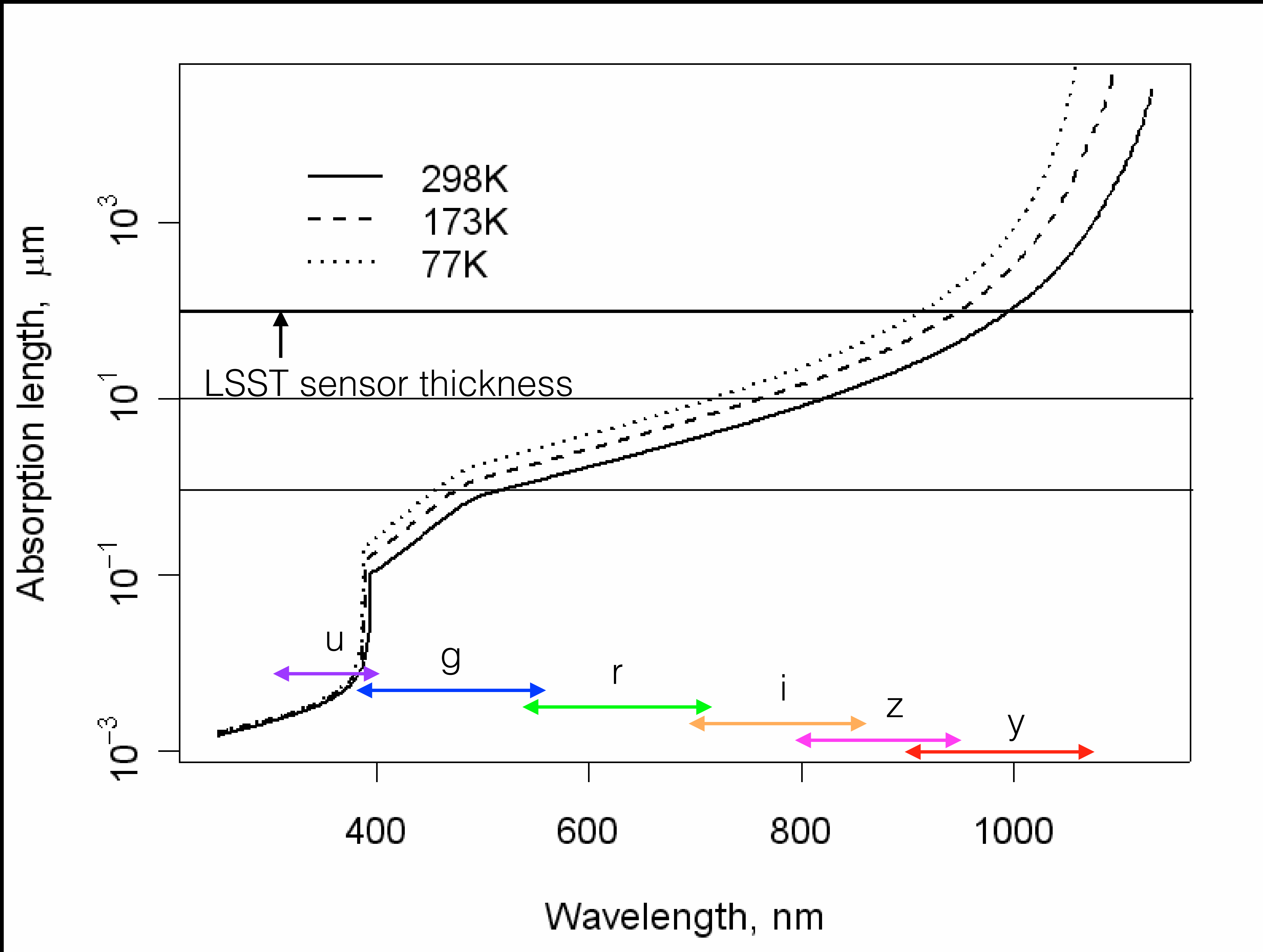
Set β_- such that CCD PSF ellipticity is -0.1 at blue edge and +0.1 at red edge.

Works out to about 1×10^{-5} arcsec^2/nm (same as before) or $de_1/d\lambda \sim 0.0014$ / nm

Toy model — wavelength-dependent ellipticity



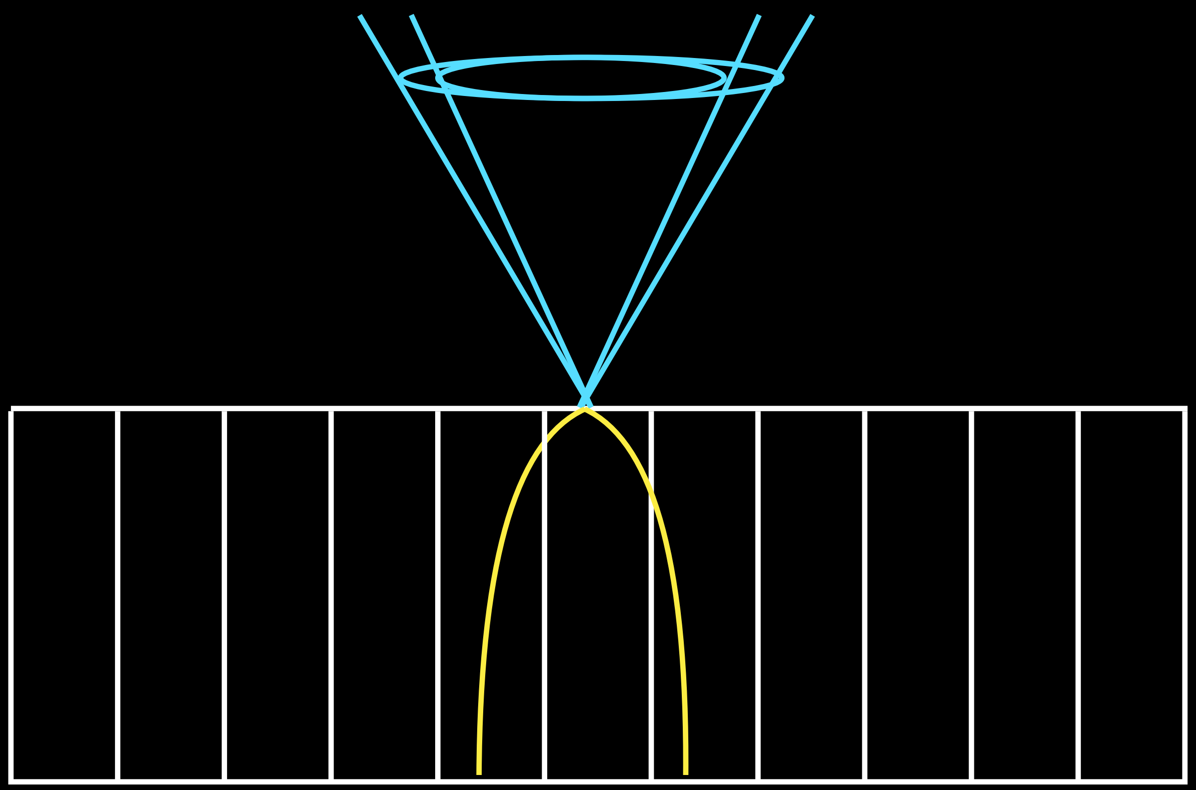
Source of CCD chromaticity



O'Connor++06

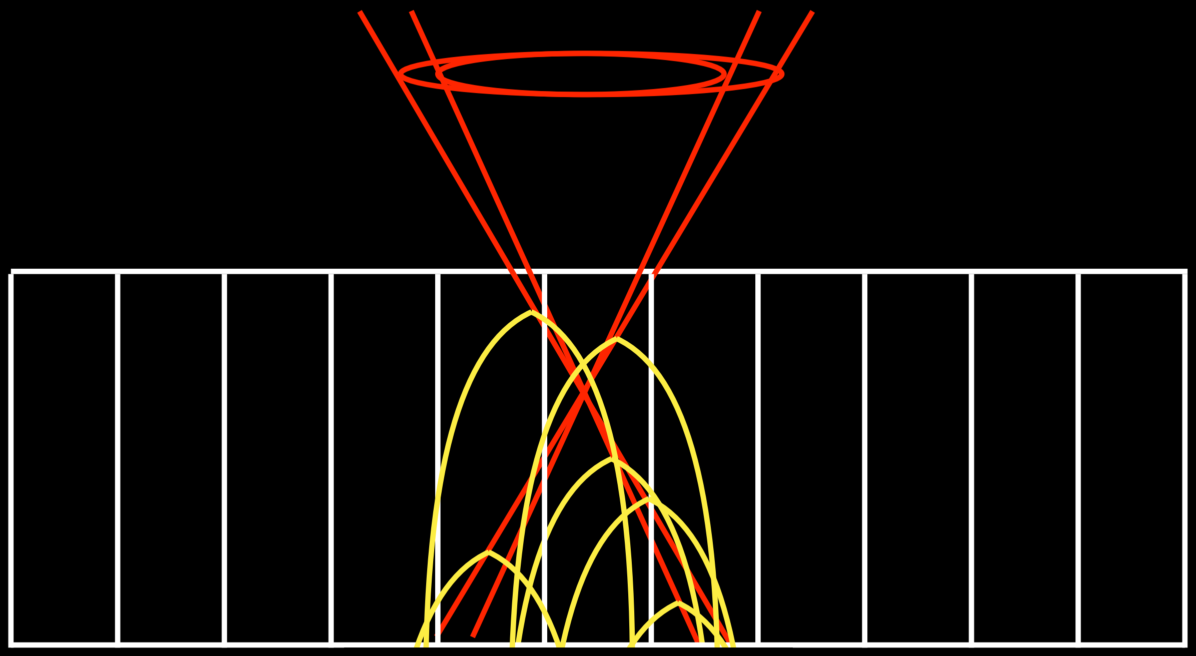
Spread in projected photo-conversion location

Blue photons
convert immediately



cartoon
for blue filter

Redder photons
convert further
into the Silicon

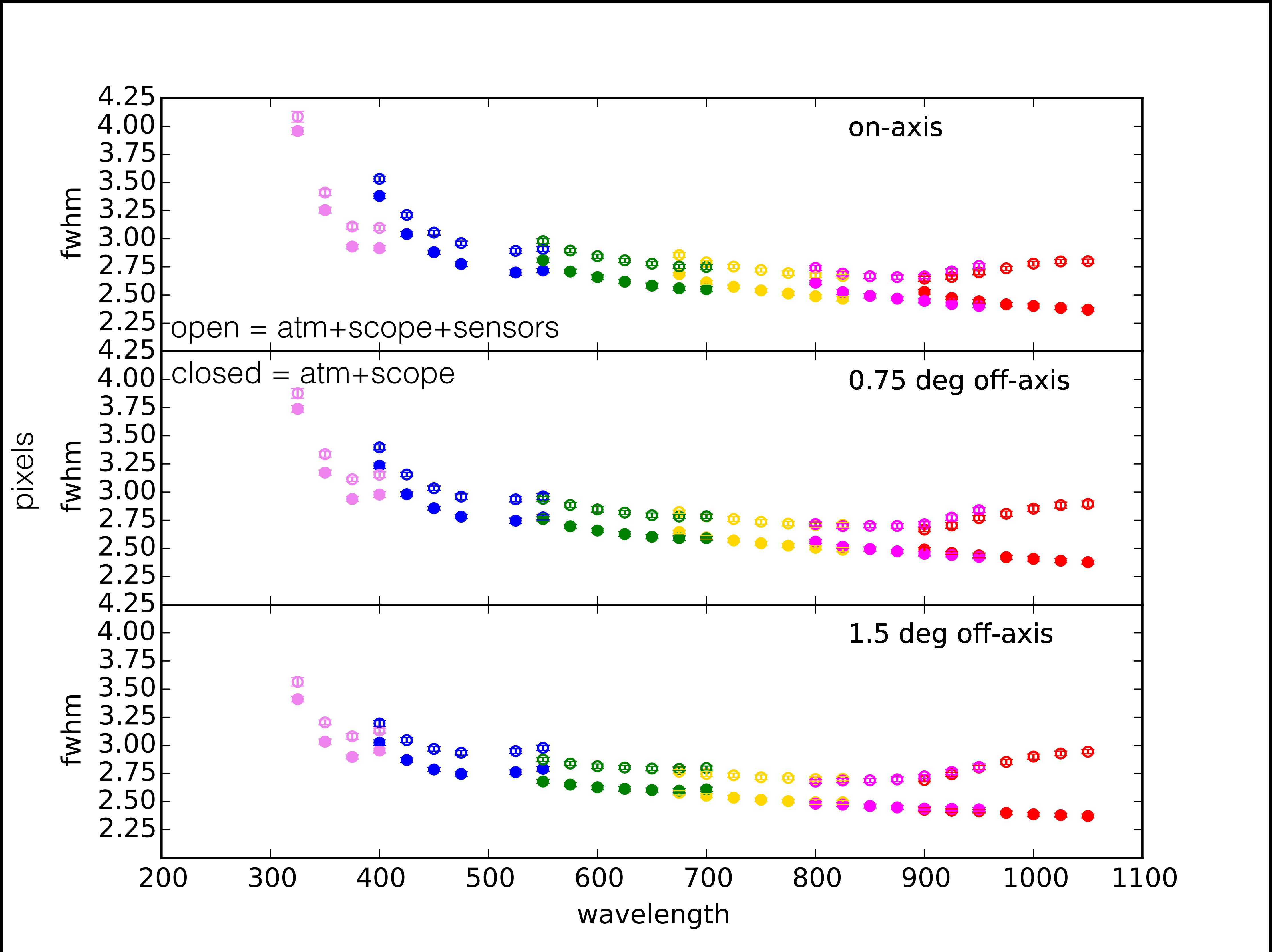


cartoon
for red filter

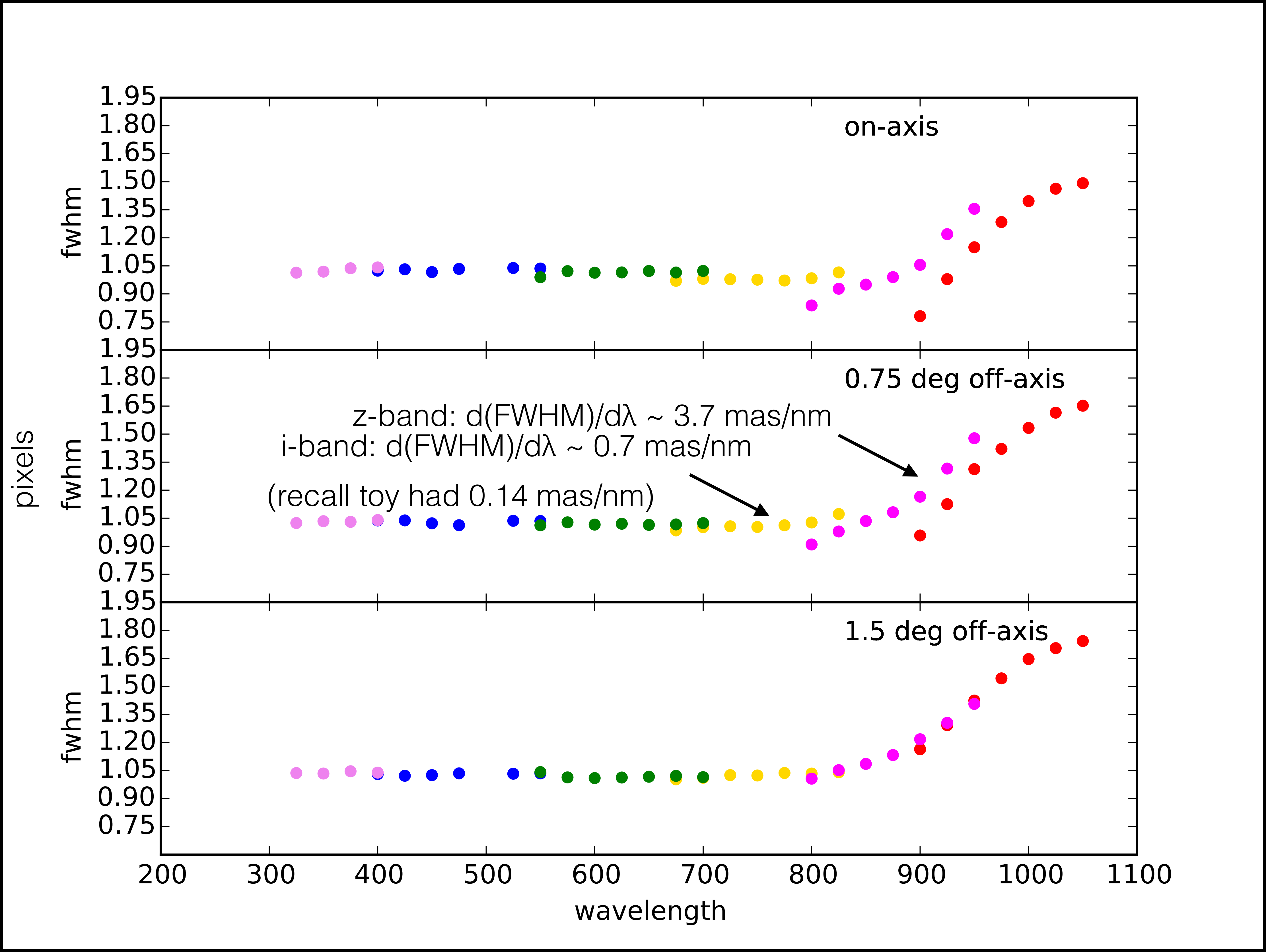
(ignoring refractive
index of silicon)

Phosim: PSF size (with and without sensor)

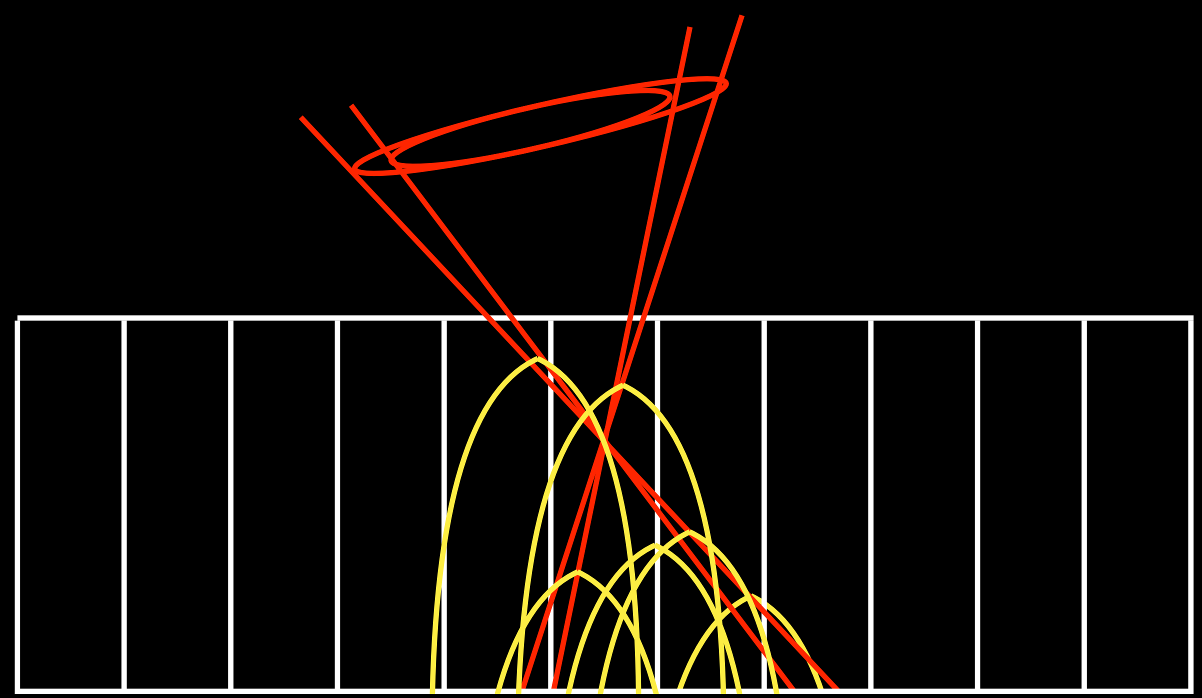
Use grid of monochromatic stars



Phosim: PSF size (sensor contribution only)



Ellipticity increases at edge of field as beam tilts.

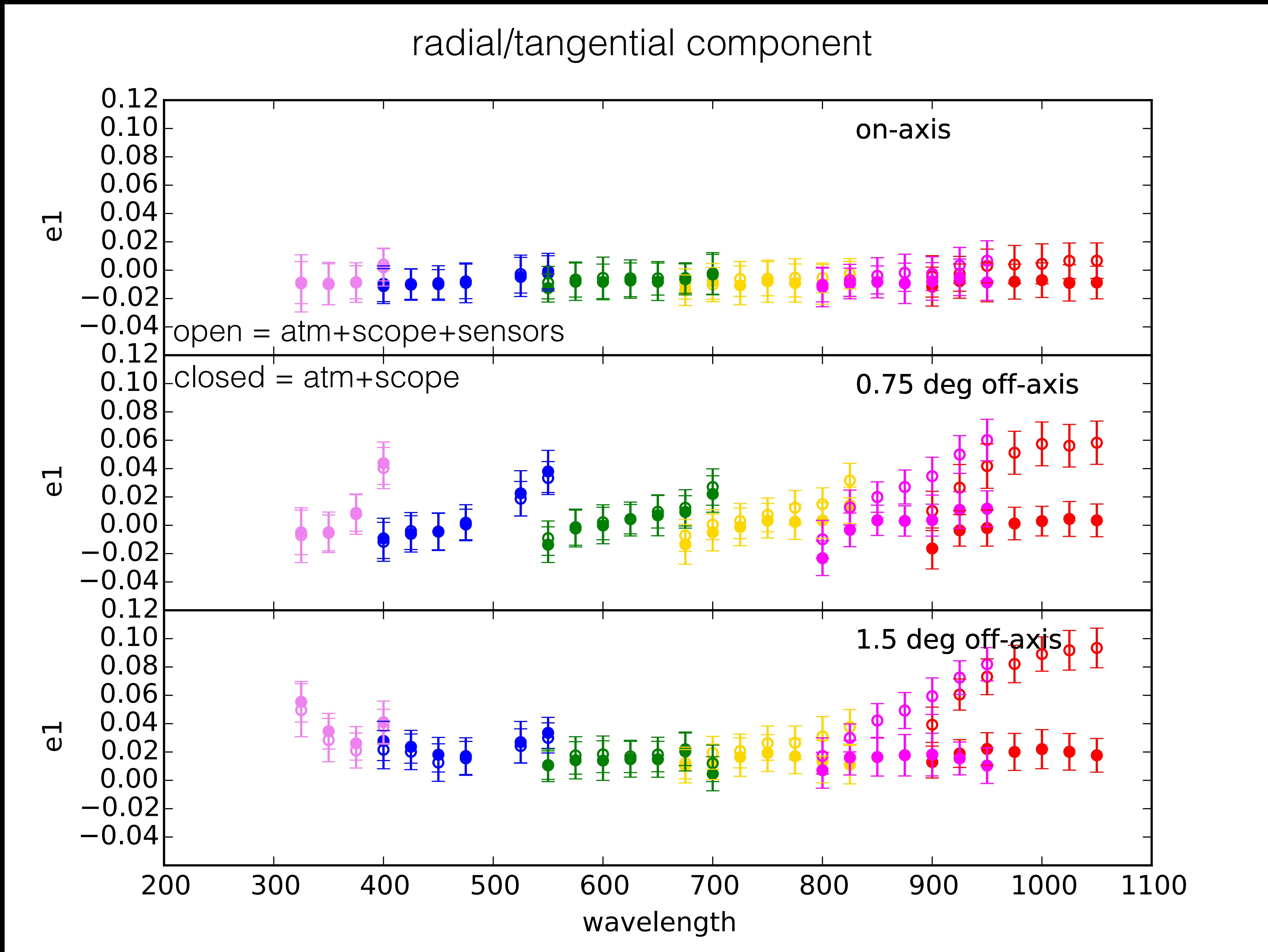


cartoon
off-axis
beam

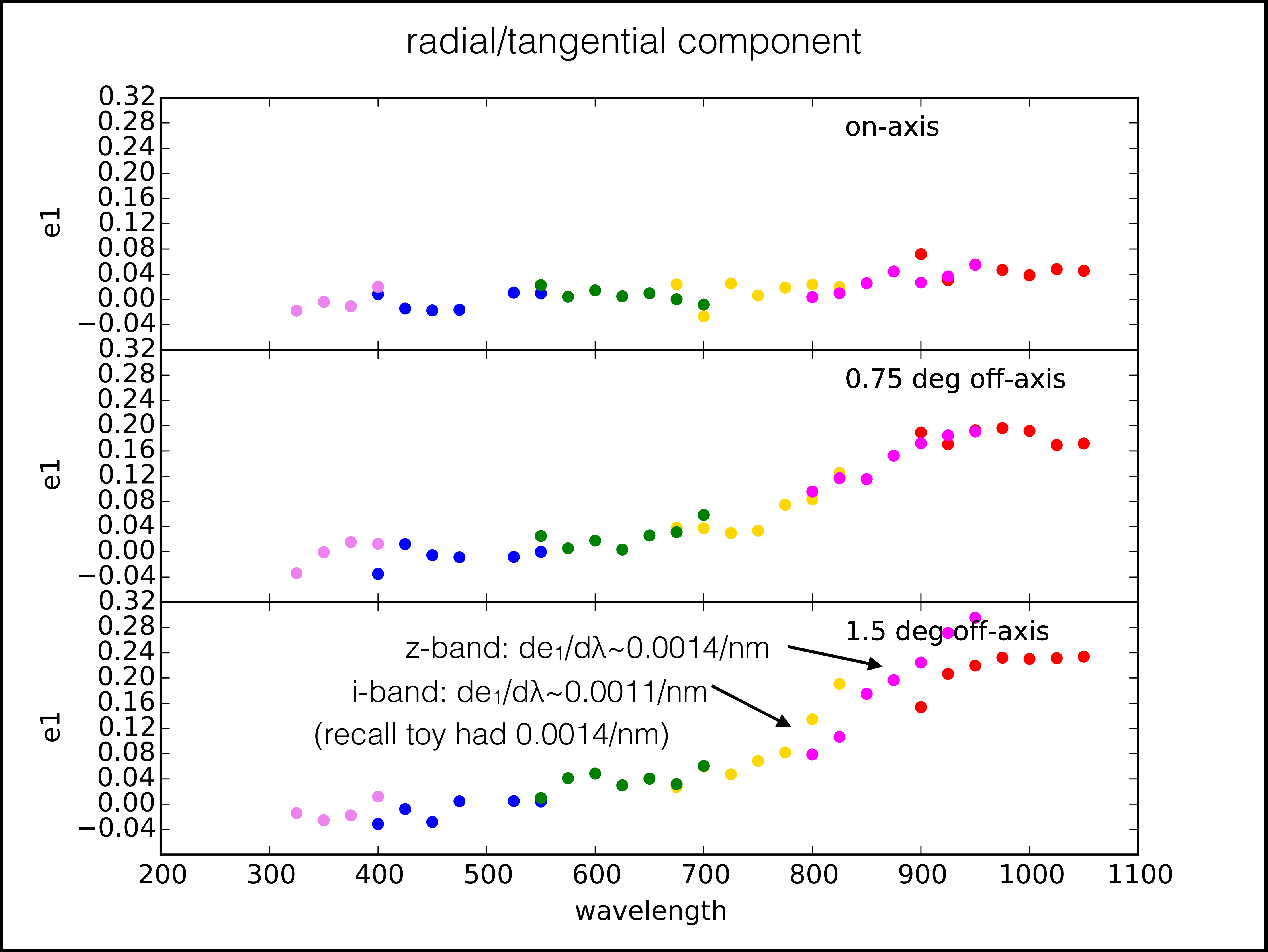
(ignoring refractive
index of silicon)

Also, reflections off front-side

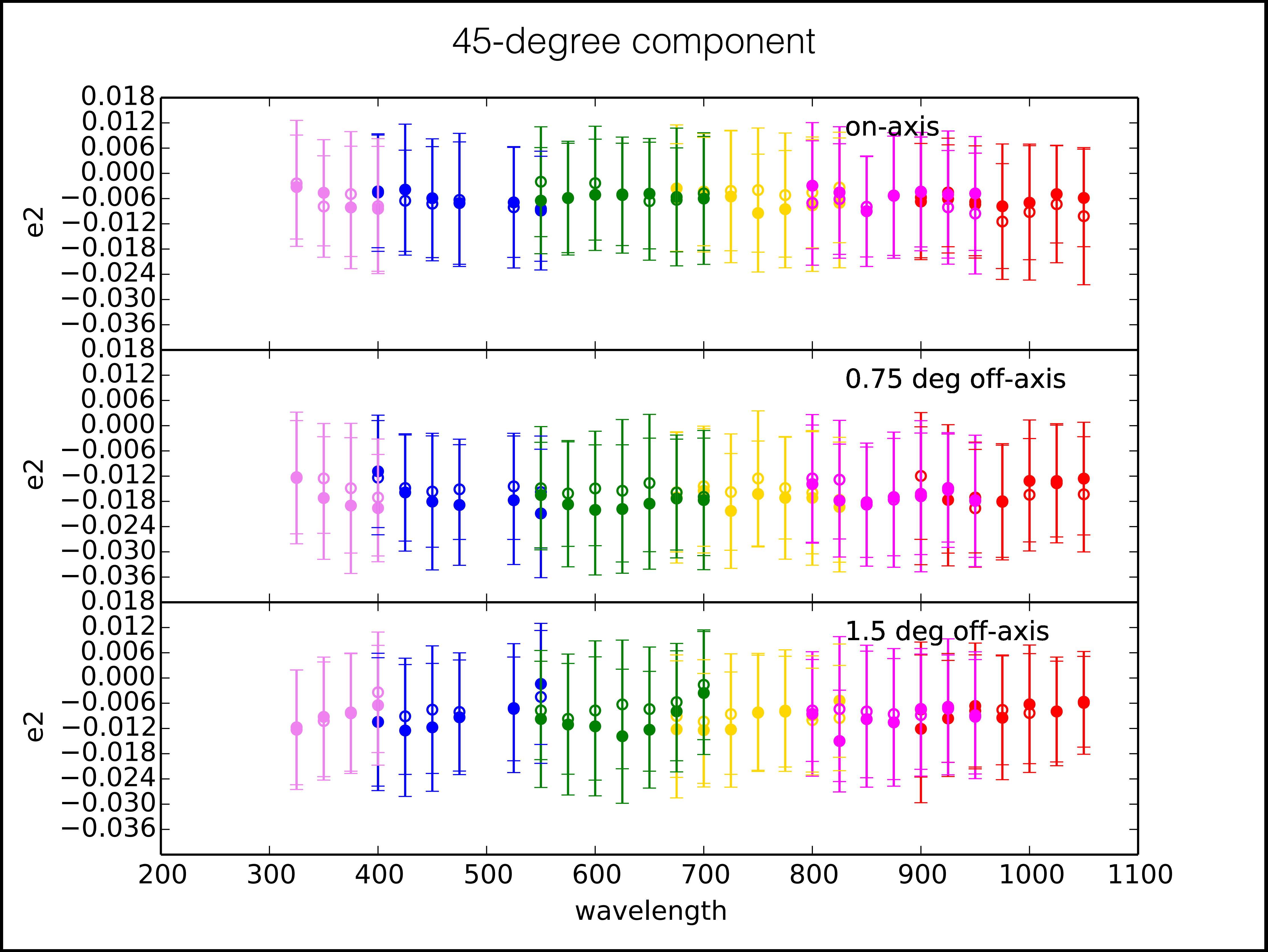
Phosim: PSF ellipticity (with and without sensor)



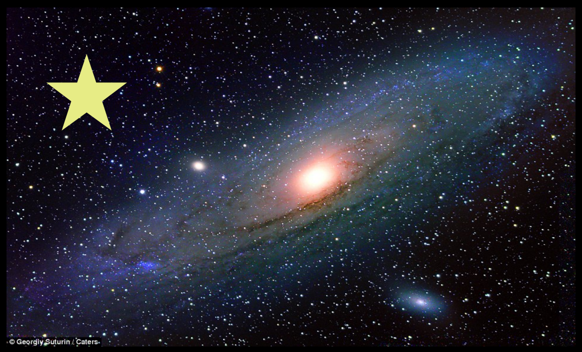
Phosim: PSF ellipticity (sensor contribution only)



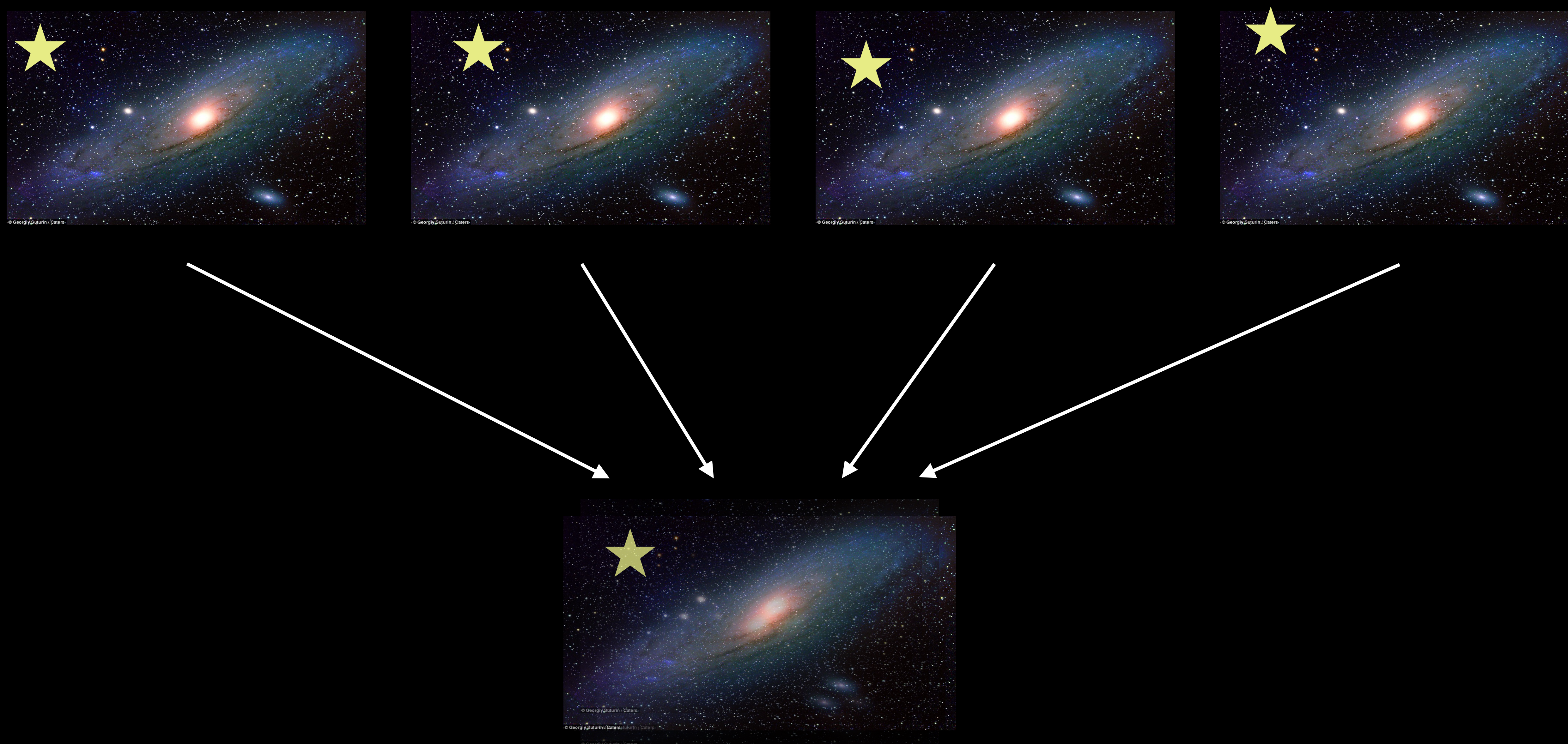
Phosim: sensor PSF ellipticity - no 45 degree component.



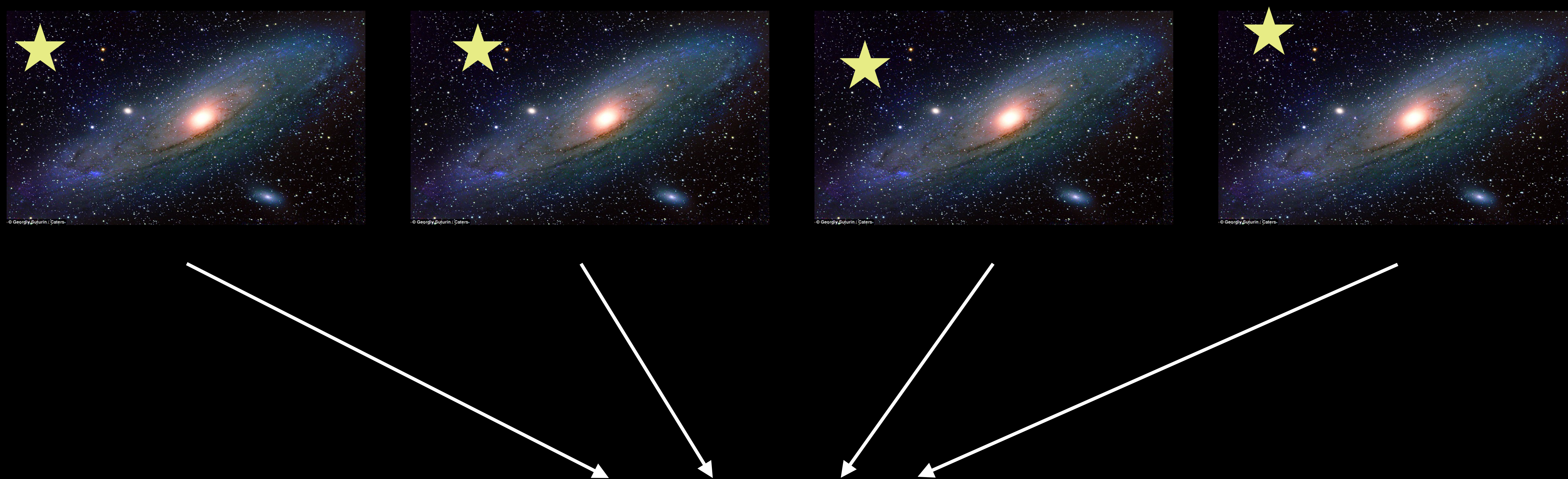
Misregistration bias - First moments matter too!



Misregistration bias - First moments matter too!

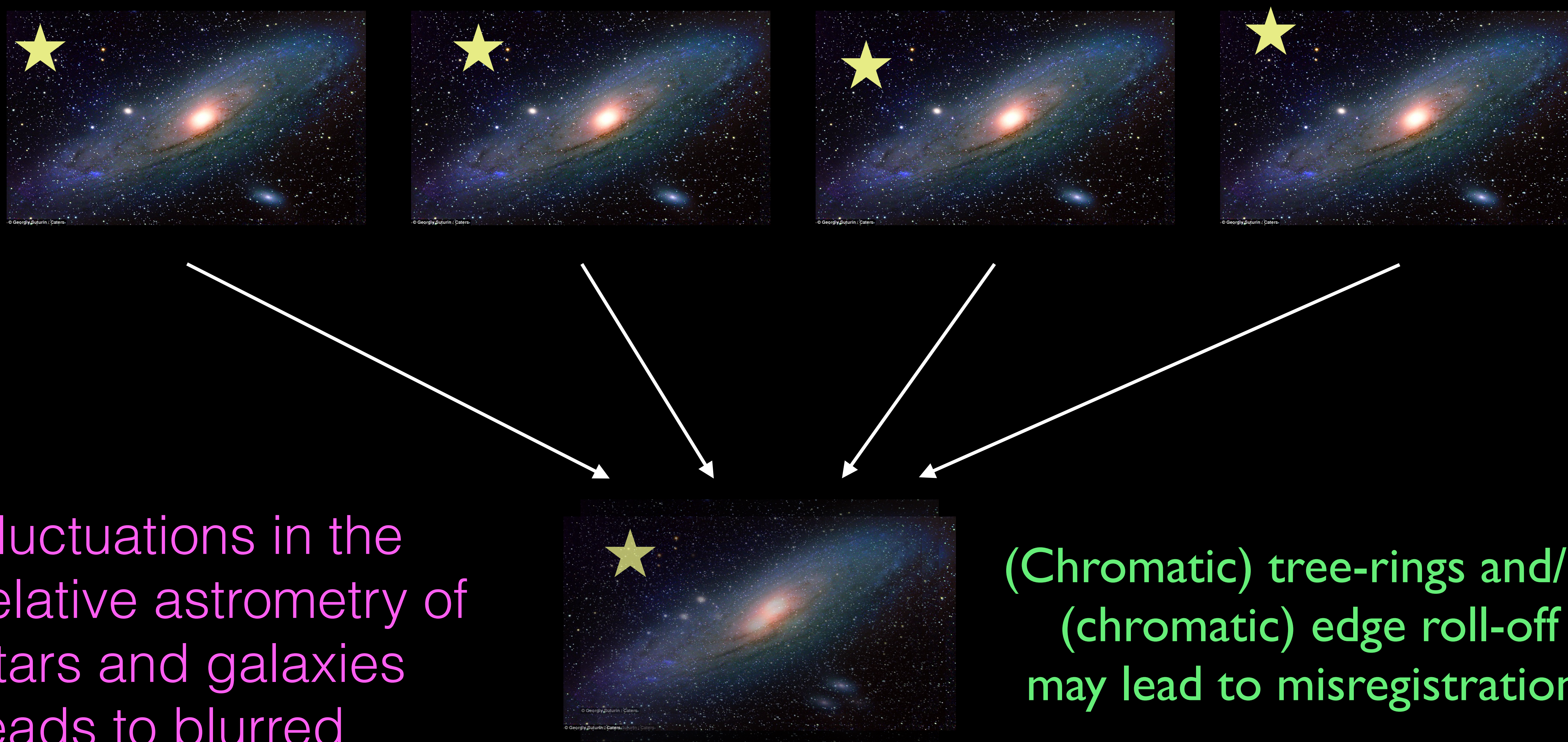


Misregistration bias - First moments matter too!



Fluctuations in the relative astrometry of stars and galaxies leads to blurred stacked galaxy image.

Misregistration bias - First moments matter too!



Fluctuations in the relative astrometry of stars and galaxies leads to blurred stacked galaxy image.

(Chromatic) tree-rings and/or (chromatic) edge roll-off may lead to misregistration.

Second moments of stacked galaxy image.

Assuming flux is the same in each epoch:

$$I_{\mu\nu}^{\mathrm{stack}} = I_{\mu\nu}^{\mathrm{single\,epoch}} + \underbrace{\langle(\mu-\bar{\mu})(\nu-\bar{\nu})\rangle_{\mathrm{epochs}}}$$

Since this term enters in exactly the same way as the PSF,

$$I_{\mu\nu}^{\mathrm{obs}} = I_{\mu\nu}^{\mathrm{gal}} + I_{\mu\nu}^{\mathrm{PSF}}$$

it can be treated as an error in the PSF:

$$\Delta I_{\mu\nu}^{\mathrm{PSF}} = \langle(\mu-\bar{\mu})(\nu-\bar{\nu})\rangle_{\mathrm{epochs}}$$

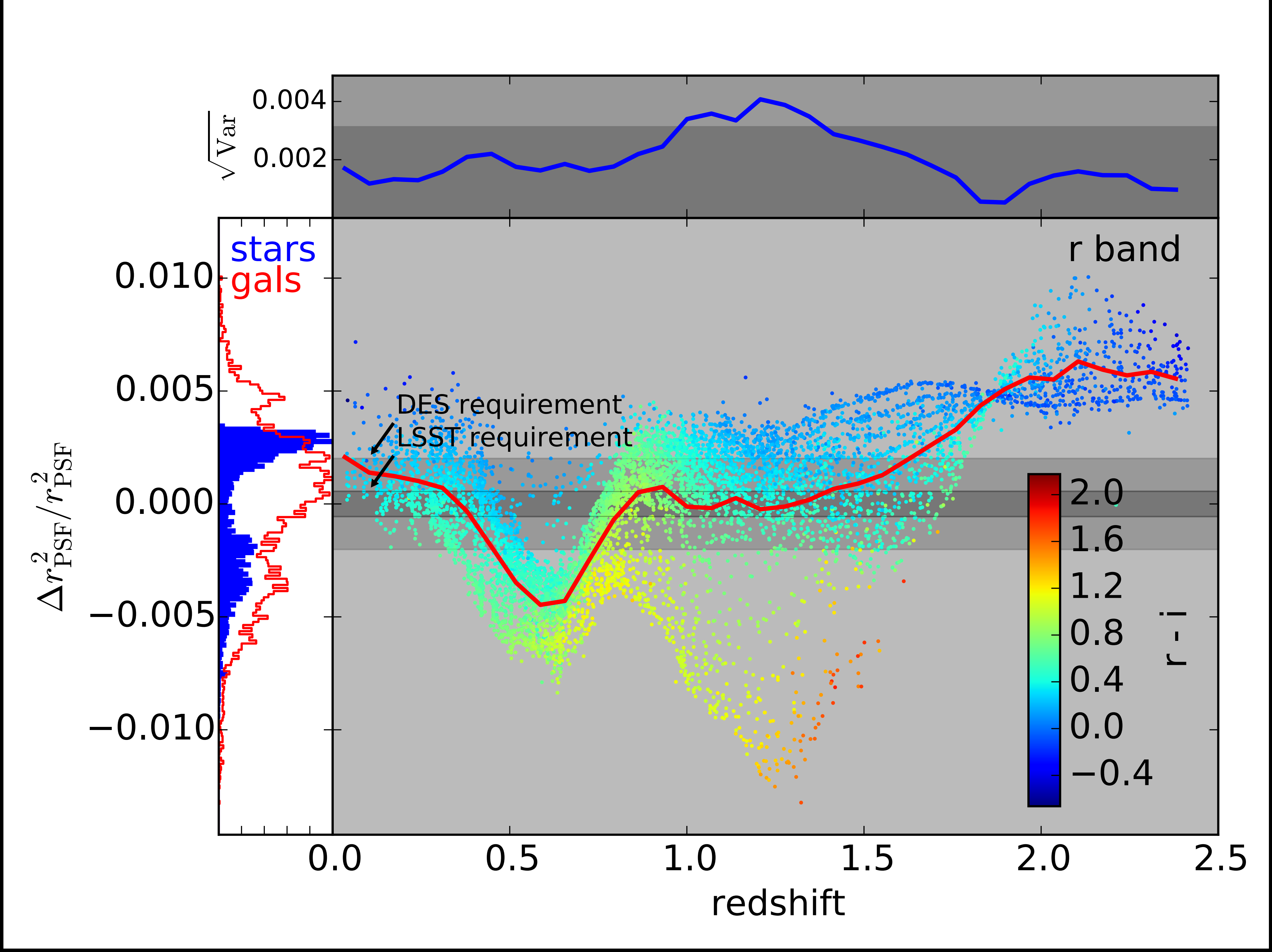
Implies the requirement:

$$\sqrt{\langle\left(\vec{x_i} - \langle\vec{x}\rangle\right)^2\rangle} < 16\ \mathrm{mas}$$

Corrections: learn SED from photometry

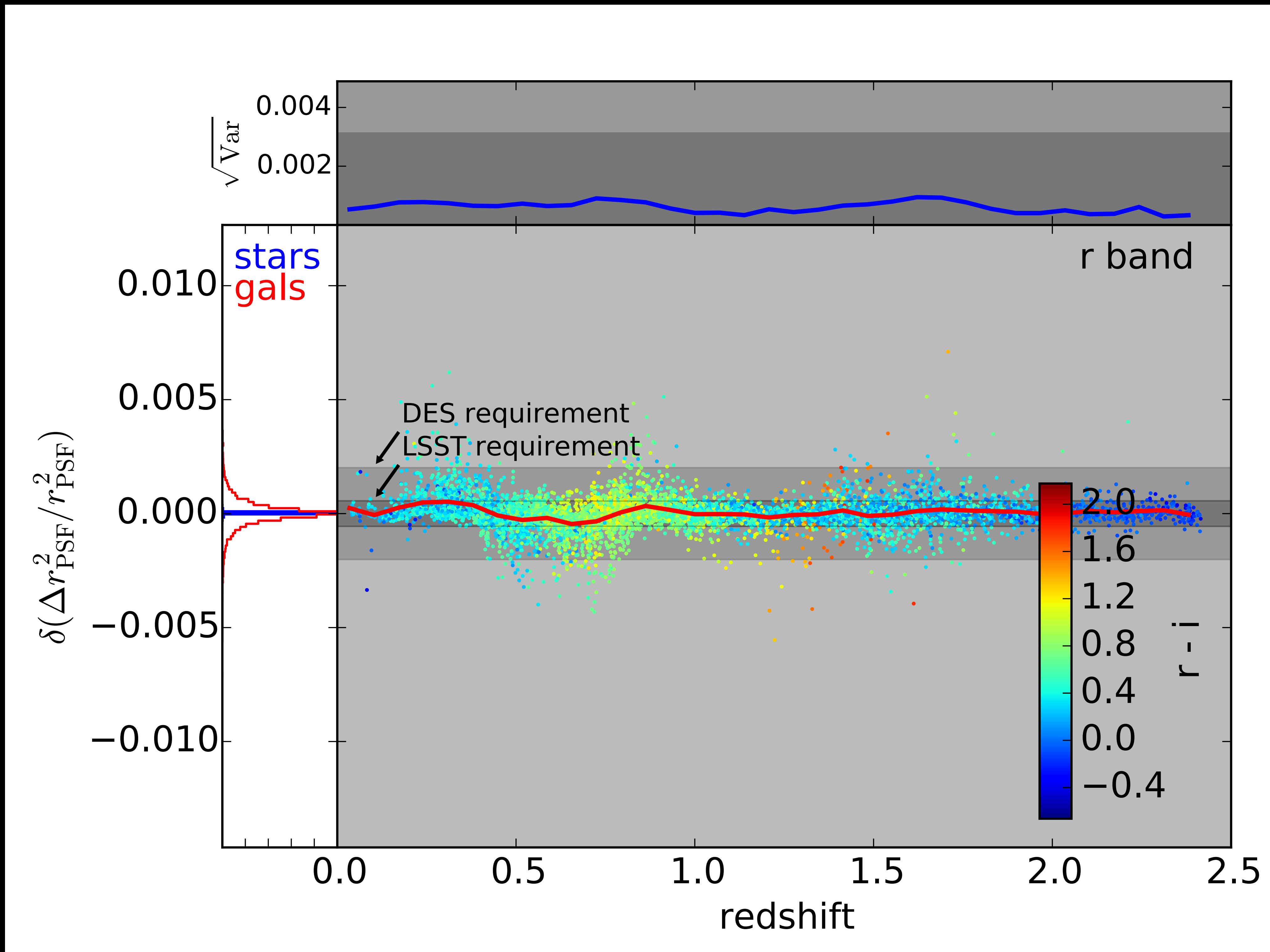
- Can correct if you know
  - PSF(λ)
  - The SED
- Train a machine-learning algorithm to predict chromatic bias as a function of photometry.
- Conceptually similar to a photometric redshift.

Corrections: learn SED from photometry



Meyers+Burchat2014 (arXiv:1409.6273)

Corrections: learn SED from photometry



Meyers+Burchat2014 (arXiv:1409.6273)

Conclusions

- Chromaticity in sensors is probably smaller than in the atmosphere or the optics, but still should be accounted for.
- Some rough numbers for LSST sensors (when individual systematic uncertainties will rival statistical uncertainties):
    - Uncertainty in d(FWHM)/dλ to ~0.1mas/nm
    - Uncertainty in d(e)/dλ to ~0.001/nm
    - Individual exposure RMS astrometric shifts ~16mas.